Reduction in Soil Penetration Resistance for Suction-assisted Installation of Bucket Foundation in Sand

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Agenda

- Concept of bucket foundation
- CPT-based method for suction installation
- 1G laboratory tests on jacking and suction installation
- Results and discussion
- Conclusions
Concept of bucket foundation

- Suction bucket foundation - concept

- Success in suction installation

Fig.1 Seepage flow around the bucket skirt [1]

Fig.2 Case studies from Universal Foundation, Denmark [2]
Agenda

- Concept of bucket foundation
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CPT-based method for suction installation

- Soil penetration resistance

\[ R_{soil} = F_{in} + F_{out} + Q_{tip} \]

- Reduction due to the seepage flow

\[
\begin{align*}
F_{in} &= \pi D_i k_f \int_0^h q_c(h) \, dh \\
F_{out} &= \pi D_o k_f \int_0^h q_c(h) \, dh \\
Q_{tip} &= A_{tip} k_p q_c(h)
\end{align*}
\]

Empirical coefficients \( k_f \) and \( k_p \)

Reduction factors: \( \beta_{in}, \beta_{out}, \beta_{tip} \)
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Test set-up and model of bucket foundation


Fig. 4 Bucket foundation model: (1) valves, (2) pore pressure transducers, (3) displacement transducer, (PP1-PP6) measurements points
1G laboratory tests on jacking and suction installation

- Soil preparation, $I_D = 90\%$
- CPT before and after installation
- Test procedure and measurements
  - Jacking installation
  - Suction installation

Fig. 5 Photos from laboratory procedure [3]
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- Concept of bucket foundation
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Empirical coefficients $k_p$ and $k_f$

- Optimization of 4 jacking installation tests

\[ R_{soil} = F_{in} + F_{out} + Q_{tip} \]

\[ F_{in} = \pi D_i k_f \int_0^h q_c(h) \, dh \]
\[ F_{out} = \pi D_o k_f \int_0^h q_c(h) \, dh \]
\[ Q_{tip} = A_{tip} k_p q_c(h) \]

\[ R_{soil} = F_{inst} \]

\[ R_{soil} = \sum_{i=1}^{4} F_{inst} \]

<table>
<thead>
<tr>
<th>Empirical coefficients</th>
<th>Lowest expected</th>
<th>Highest expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_p$</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>$k_f$</td>
<td>0.001</td>
<td>0.003</td>
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</table>

Tab.1 Recommended values of empirical coefficients for sand from DNV

<table>
<thead>
<tr>
<th>Chosen coefficient for optimization</th>
<th>Value of $k_f$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.004</td>
<td>Lehance et al. 2005 [4]</td>
</tr>
<tr>
<td></td>
<td>0.0023</td>
<td>Senders and Randolph 2009 [5]</td>
</tr>
<tr>
<td></td>
<td>0.0053</td>
<td>Andersen 2008 [6]</td>
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</tbody>
</table>

Tab.2 Chosen values of $k_f$ for optimization

<table>
<thead>
<tr>
<th>Test no.</th>
<th>$k_f$</th>
<th>$k_p$</th>
<th>$R^2$</th>
</tr>
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<tbody>
<tr>
<td>06</td>
<td>0.0023</td>
<td>0.38</td>
<td>0.991</td>
</tr>
<tr>
<td>07</td>
<td>0.0023</td>
<td>0.36</td>
<td>0.998</td>
</tr>
<tr>
<td>08</td>
<td>0.0023</td>
<td>0.39</td>
<td>0.998</td>
</tr>
<tr>
<td>10</td>
<td>0.0023</td>
<td>0.33</td>
<td>0.994</td>
</tr>
</tbody>
</table>

Fig.6 Soil resistance compared with installation load (test no.06)

Tab.3 Chosen values of empirical coefficients
Empirical coefficients $k_p$ and $k_f$

- Comparison of calculated resistance with applied load

Fig. 7 Test no. 06 - $k_p = 0.38$, $k_f = 0.0023$

Fig. 8 Test no. 07 - $k_p = 0.36$, $k_f = 0.0023$

Fig. 9 Test no. 08 - $k_p = 0.39$, $k_f = 0.0023$

Fig. 10 Test no. 10 - $k_p = 0.33$, $k_f = 0.0023$
Soil resistance reduction factors $\beta_{in}, \beta_{out}, \beta_{tip}$

- $\beta$ - factors

$$\beta_{in} = 1 - r_{in} \cdot \exp\left(\frac{p}{p_{crit}}\right),$$

$$\beta_{tip} = 1 - r_{tip} \cdot \exp\left(\frac{p}{p_{crit}}\right),$$

$$\beta_{out} = 1$$

- Critical suction pressure

$$i_{exit} = \frac{p}{s\gamma_w}$$

$$\left(\frac{s}{h}\right)_{exit} = 1.25 \left(\pi - \text{atan}\left(2.5 \cdot \left(\frac{h}{D}\right)^{0.74}\right)\right) \cdot \left(2 - \frac{1.8}{\pi}\right)$$

$$i_{crit} = \frac{\gamma'}{\gamma_w}$$

$$\frac{p_{crit}}{\gamma'D} = \left(\frac{h}{D}\right) \cdot \left(\frac{s}{h}\right)$$

Adjusted for:
- boundary conditions
- increased inside soil permeability

Fig. 11 Applied pressure for all suction installation tests

Optimization of 6 suction installation tests
<table>
<thead>
<tr>
<th>Test no.</th>
<th>For $k_p = 0.33$</th>
<th>For $k_p = 0.39$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$r_{in}$</td>
<td>$r_{tip}$</td>
</tr>
<tr>
<td>01</td>
<td>1.0</td>
<td>0.11</td>
</tr>
<tr>
<td>02</td>
<td>1.0</td>
<td>0.14</td>
</tr>
<tr>
<td>03</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>04</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>05</td>
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<td>0.1</td>
</tr>
<tr>
<td>09</td>
<td>1.0</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Tab.4 Chosen values of reduction factors

\[
\beta_{in} = 1 - r_{in} \cdot \exp \left( \frac{p}{p_{crit}} \right),
\]

\[
\beta_{tip} = 1 - r_{tip} \cdot \exp \left( \frac{p}{p_{crit}} \right),
\]

\[
\beta_{out} = 1
\]
Comparison between the suction and jacking installation

Fig. 16  Test no.06 – jacking installation

Fig. 17  Test no.01 – suction installation
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Conclusions

- Success of laboratory tests for suction installation
  - reduction in soil penetration resistance
  - loosening of inside soil plug

- CPT-based method for calculation of soil penetration resistance
  - suggested values for parameters $k_p$ and $k_f$
  - reduction in resistance: factors $\beta_{in}$, $\beta_{tip}$

- Critical suction
Thank you for your attention!

References:


